Analog Integrated Circuit Design
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Lecture No - 5
Opamp Realization using Controlled Sources; Delay in the Loop

Hello everyone, this is the fifth lecture of analog integrated circuit design. We have learnt few things, so far. Firstly, we have learnt how to make a negative feedback amplifier, using an integrator. If you want an output to be k times, larger than the input, then you compare v naught divided by k to the input and integrate the output. Integrate the difference, until the output reaches the correct value. So, if the input is the constant, and if you wait long enough, the output will reach exactly the right value. This is the basic negative feedback amplifier. We have also done quantitative analysis of this amplifier and seen how the time constant and the bandwidth relate to the parameter of the integrator which is the speed of integration or omega u.

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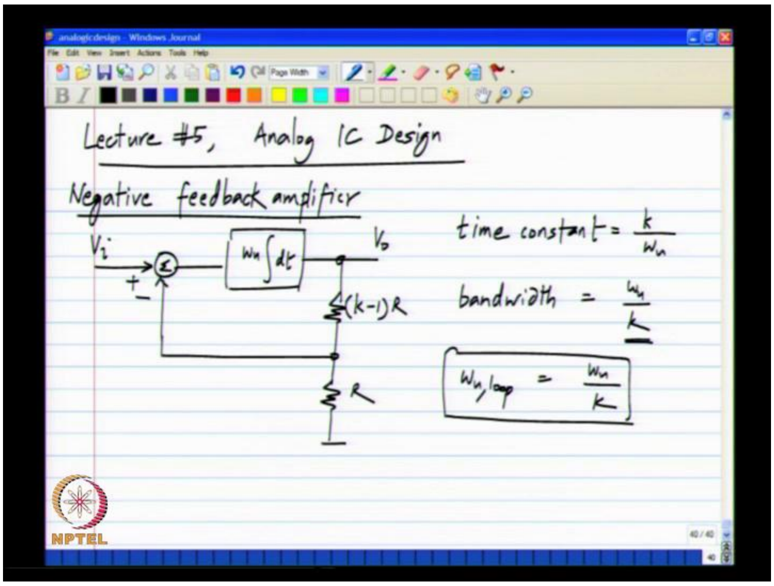

So, in this amplifier, the time constant is k by omega u and the bandwidth is omega u by k, where omega u is the unity gain frequency of the integrator. It is the frequency at which, the gain of the integrator is unity. The magnitude of the gain of the integrator is unity. We also investigated, why this omega u by k, comes about, that we did by trying to quantify the amount of negative feedback. What we evaluated was the loop gain. If you look at the loop gain, the unity loop gain frequency is omega u by k. And that is why, it turns out to be the bandwidth of the system. Below omega u by k you have significant negative feedback. Above omega u by k, you do not have significant negative feedback. So, these are the things that we have learnt.

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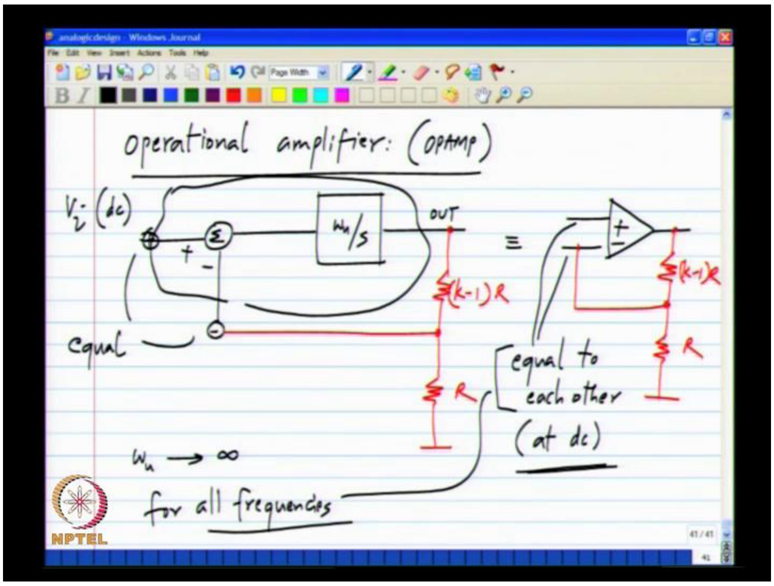

So, for and another concept that we introduced was the concept of the opamp. So, an opamp is nothing but, the combination of being able to take the difference and integrating it. So, this entire block is known as the opamp. This is the output terminal of the opamp. This is the plus terminal of the opamp. This is the negative terminal of the opamp. So, we make a negative feedback amplifier around the opamp and that is the same as this one. We have said that, when V i is a constant and steady state is reached, these two voltages are equal. So, which means that, this voltage and this voltage are equal to each other at dc. So, this brings us to the concept of the ideal opamp.

Now, if you set omega u to infinity, then these two will be equal to each other for all frequencies. That is what an ideal opamp is. An ideal opamp is something that, when place the negative feedback it maintains the two input terminals to be exactly equal. And other it happens is that, it is comparing the difference between the two terminals and then integrating the error. Integrating the difference and then driving the output with it in a direction that will minimize the error.

So, if omega u is infinity, the minimum value of the error is nothing, but zero. So, these two voltages will be equal for all frequencies. So, this is what an opamp is and as we go through this course, will be learning how to design the opamp at the transistor level.

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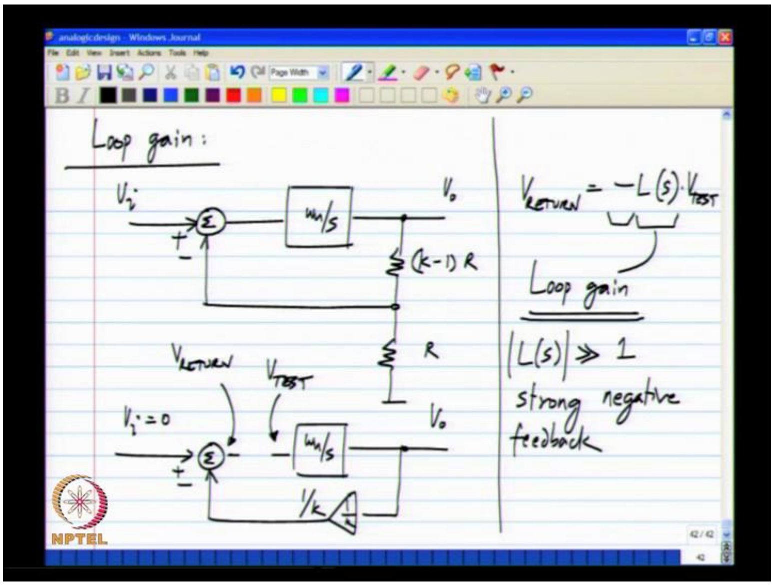

So, another concept that was introduced was the loop gain. So, we have our negative feedback amplifier, which we have been drawing in this form. This can be equally represented by using a block, instead of a voltage divider. The block as on attenuation of 1 by k . So, you have to quantify the loop gain. Essentially, what we have trying to do is, how strong their negative feedback is. In order to do that, we said the input to be zero and then see how much the loop amplifiers the signal, that is injected into the loop.

So, we said V i to be zero. We break the loop, apply a test voltage here and see what comes back here. So, what comes back will be some multiple of what is injected. We define it with the negative sign, because we are dealing with negative feedback systems. The factor that is multiplying it, this is what the loop gain is. So, if the loop gain is very large, there is strong negative feedback and the system behaves as you expect from the principles of negative feedback.

For instance, when the magnitude of the loop gain is very large in this particular case, the gain of the amplifier will be k. This happens for frequency is much smaller than omega u divided by k and because of practical limitations, there will be frequencies where the magnitude of l of s is less than 1. In this case, there is weak feedback and in this case the system will behave non-ideally. So, these are the things that we have learnt so far.

Now, we will go and try to make some of the other types of amplifiers using the opamp. What we have made so far is voltage control, voltage source or a voltage amplifier. The output is a voltage and the input is a voltage, but it does not have to be like that. You can have an input current or you can translate an input voltage to an output current. So, we will do those things with an opamp. And we will see how to do that.

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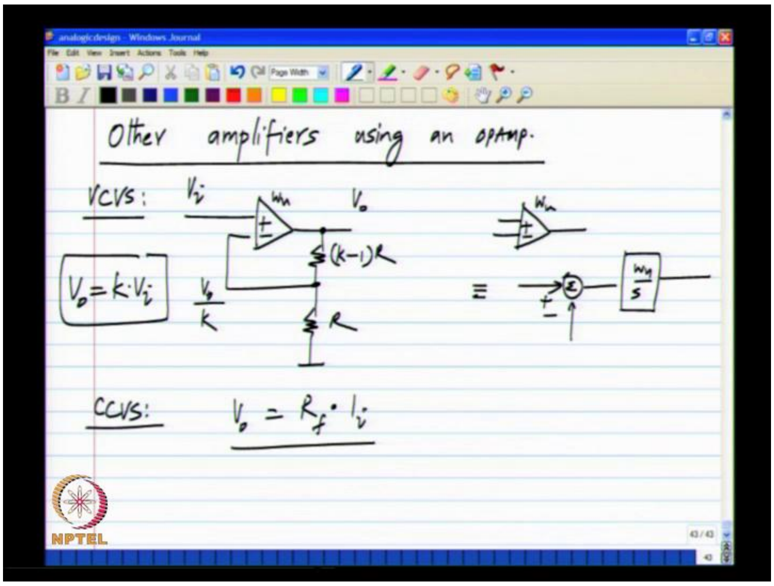

So, what we have so far is a voltage control, voltage source. Where, this stands for and omega u is an important parameter of the opamp. That will be given in the opamp data sheets and so on. So, in this case, what we did was, we took the difference between V i and V naught by k, integrated the difference to get the output. So, let us see, we want to make instant a current control voltage source.

The our voltage control, voltage source has a relationship, which is v naught this k times V i. A current control voltage source will have a relationship which is, V naught to be some quantity, which has dimensions of resistance times I i. Where I i, is the input current. So, we have to, we have to achieve this relationship using negative feedback. So, let us see how to do that.

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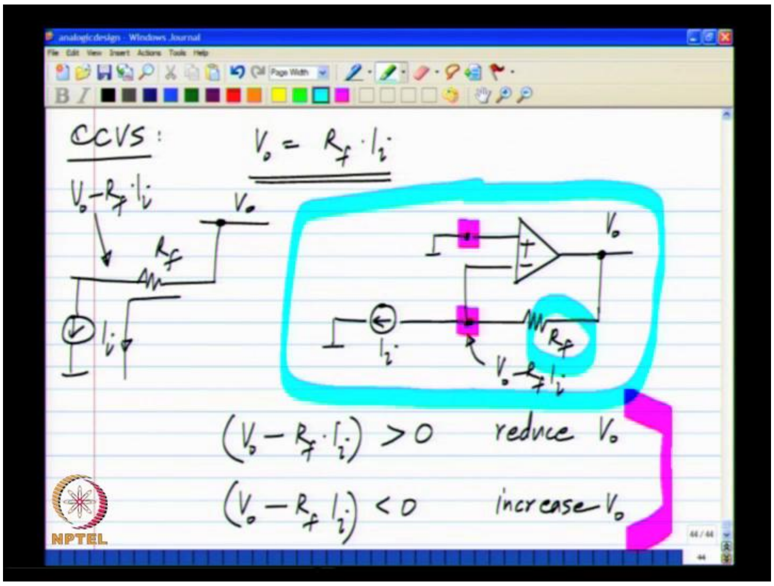

So, when I say we had to do this using negative feedback, we have to find an appropriate difference, that will integrate and drive the output voltage in the right direction. The way our opamp is, it takes the difference between these two voltages. It operates on the difference between input voltages. So, we have to setup our goal in such a way, that we look at the difference between two voltages and then drive the output voltage. So, the output voltage in our case is nothing but, V naught. That is the output that we want to drive.

Looking at this relationship, I want V naught to be equal to R f times I i. In other words, I can also write it as, if V naught minus R f times I i is more than zero, then I have to go on reducing the output voltage. If V naught minus R f I i is less than zero, I should go on increasing the output voltage. So, essentially this is the error that I have to integrate V naught minus R f I i in the appropriate polarity.

So, the first thing I have to do is, to be able to obtain this voltage V naught minus R f I i. That is a very easy thing to do. With another certain voltage V naught, somewhere and I have a current I i that is the input quantity, I can easily get V naught minus R f I i by using this arrangement. So, the current I i flows through R f and the voltage at this point will be V naught minus R f times I i. So, I will do that here. So, at this point, I have V naught minus R f I i. I have to compare this to zero.

So, out of these two terminals, one of them has to be connected to V naught minus R f times I i and other one has to be connected to zero. And they should be connected so that, if V naught minus R f I i is more than zero, I have to reduce the value V naught. That is the difference, that is being integrated has to be negative in this case. So, this means that, I have to connect it up like that. What happens is, if V naught minus R f I i is more than zero? Note that V naught minus R f I i is connected to the negative terminal and zero to the positive terminal.

So, if the negative terminal is more than the positive terminal, the output voltage goes on decreasing and vice versa. If the negative terminal is less than the positive terminal, the output voltage goes on increasing. It is exactly the action, that is described here. This particular amplifier is one which takes the input current and converts it to an output voltage, because the input is a current and the output is a voltage. Again the or the ratio between the output voltage and the input current as dimensions of resistance. It is not a dimension less gain, but it has dimensions of resistance and that ratio is nothing but, R f.

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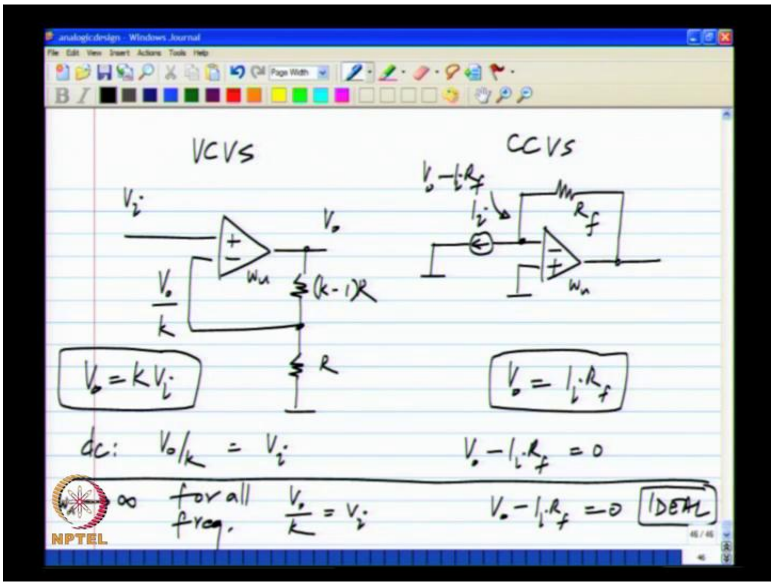

Now, I will redraw this in a way that is more familiar and how it is normally drawn. It is usually drawn with the resistor being on top. So, again if we imagine that I i is a D C, then, the output will stop changing, only when this point is exactly at zero, because if this point is more than zero, the output will go on reducing. If it is less than zero, the output will go on increasing. The only way the output will reach a steady value, a constant value is when, this is exactly equal to zero. When this is exactly equal to zero, the output has to be equal to I i times R f.

So, we can use a negative feedback to make a current control voltage source. You can of course, also use negative feedback to make another kinds of control sources, which we will see later on in the course. That is voltage control current source and a current control current source. So, now you are familiar with the opamp and two types of opamp circuits. Again let me emphasize that, opamp is nothing but, a block that takes the difference between two voltages and integrates the difference to give you the output.

Let us say the opamp has a unity gain frequency, omega u. So, the voltage at the other terminal of the opamp, here is V naught by k. Here it is V naught minus I i R f and for DC, V naught by k equal to V i, this case. And V naught minus I i R f equal zero, in this case. If omega u goes to infinity, then for all frequencies V naught by k equals V i. And V naught minus I i R f equals zero. So, this represents the ideal case, where the relationships V naught equals k V i and V naught equals I i R f, these hold for all frequencies.

So, if you want to imagine an ideal case, where you have an ideal voltage control voltage source using negative feedback, using an opamp or an ideal current control voltage source, you imagine an ideal opamp, where the ideal opamp is nothing but, the opamp with omega u being infinity.

So, we have now learnt the concept of negative feedback, how to make amplifiers with it and how they behave. Also for the voltage control voltage Source, that is the amplifier here on the left side, where we have evaluated the time constant and the bandwidth. So, we know how it behaves in the time domain and the frequency domain. Exactly the same thing can be done for the other amplifier and we will see that the results are similar. Now going forward, what we need to know is the, how to implement the opamp. So, far we have been putting it down as a block diagram, saying that we can make an integrator. So, the next thing is to see how to make an integrator. So, that we can have the opamp circuit in practice.

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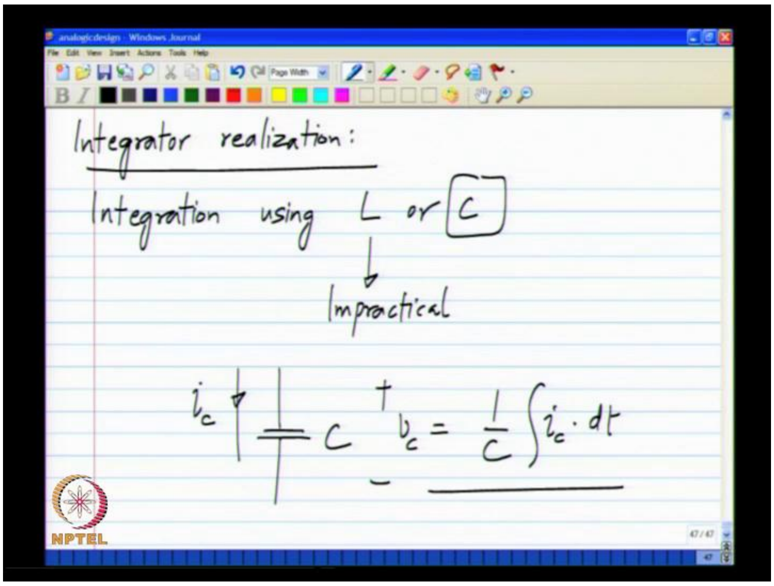

Now, how do we realize an integrator, if we look at the basic components, we have r l and c and out of this, either l or c give you a relationship which can be an integral capacitor integrates the current, to give you a voltage. The inductor integrates the voltage to give you a current. But in practice, inductors are bulk here and in harder to make. Very large values of inductors are impossible to make on integrated circuit. So, we have to use a capacitor for integration. So, l is typically impractical. So, we have to use the capacitor.

Now, we have a capacitor C and a current i c, flowing through it. The voltage across the capacitor is given by 1over C, integral of the current with respect to time. The integral of the current with respect to time is charge and the voltage is charge divided by the capacitors. Now, in our case, we want to take the difference between two voltages and the output voltage should be equal to the integral of the difference between two voltages. But what the capacitor integrates is a current. So, we first have to convert the difference between the two voltages into a proportionate current and then integrate the current.

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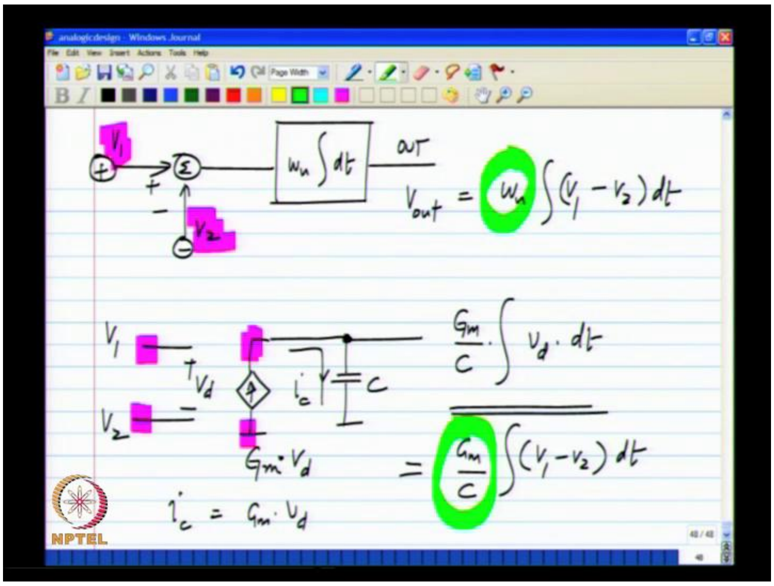

I will name this V 1 V 2 and I want to integrate the difference. This is my opamp, the plus and minus and the output terminals. So, if I choose to implement the integration with the capacitors, then this voltage will be 1 over C integral of i c d t, where i c is the current flowing through the capacitor. Now we would like i c to be related to the difference between V 1 and V 2. The way to do that is, to use a voltage control current source which I will show it as a symbol.

We have not shown, how to implement the voltage control current source, we will do that later. But right now, we can imagine that we will be able to make the voltage control current source and we will deal with it at a block diagram level. Let me call this, upper case G m, to denote that it is a trans conductance and if I have voltage is V 1 and V 2, the control current source is G m times V d, where V d is the difference between V 1 and V 2. That is, I have a voltage V 1 voltage V 2 and I have this control current source, whose current there is proportional to the difference between V 1 and V 2. It is proportional to V d, which is the difference between V 1 and V 2. That current flows through this capacitor.

So, the output voltage of the capacitor now is. So, i c is given by G m time V d. So, the output voltage of the capacitor is G m by C integral V d d t or G m by C integral of V 1 minus V 2 d t. Now, if you look at the relationship corresponding to the upper figure, the output voltage V out is omega u integral V 1 minus V 2 d t. So, if you compare the terms. So, obvious that omega u is G m by C. So, you can also check the dimensions and see that it is of correct dimensions. If you use a voltage control current source, whose proportionality constant is G m and pass its current through a capacitor C, you will realize an integrator whose unity gain frequency is G m by C.

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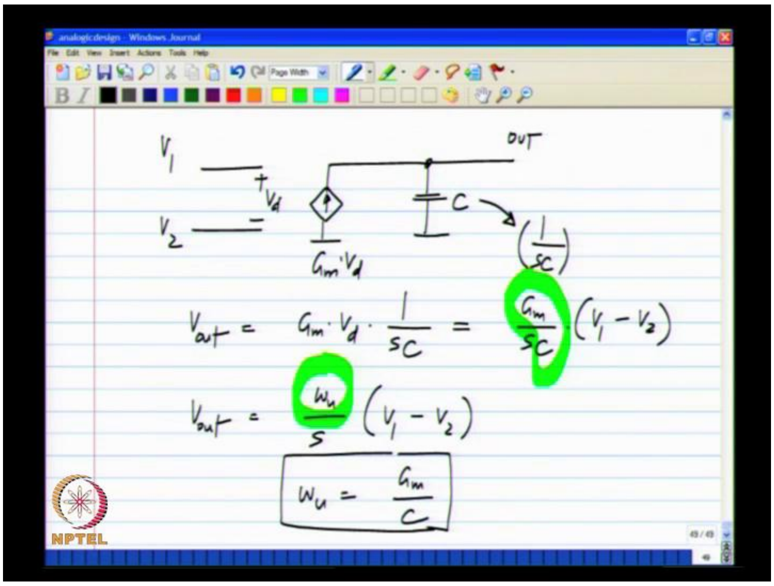

The same can be very easily seen in the frequency domain as well. So, if I have V 1 V 2 and I have a control current source G m V d. I pass it through a capacitor. I want to find out the output voltage. I can do this in the Laplace domain by replacing C with in impedance 1 by S C. Now, the voltage across the capacitor is nothing, but the current flowing through the capacitor times the impedance of the capacitor. The current flowing through the capacitor is G m V d and the impedance of the capacitor is 1 by S C. So, this is basically equal to G m by S C times V 1 minus V 2. Now, we know that, the relationship for the opamp is omega u by s.

Where, omega u is the unity gain frequency of the opamp times V 1 minus V 2. So, again we easily see that omega u is nothing but, G m by C. So, if you want to make an integrator of a certain unity gain frequency omega u, you have to have your G m and the capacitor c such that, G m by c equals omega u. You also see that, to increase the value of omega u, we said earlier that to reduce the time constant or to increase the bandwidth you have to increase the value of omega u. To do that, you have to either increase G m or decrease the value of C.

Now frequently, it is not possible to decrease the value of C, beyond a certain minimum limit. So, you will have to increase the value of G m. So, in practice this turns out to increase the power dissipation. So, we already see some constraints, that will lead to practical difficulties. That you cannot increase the value of omega u indefinitely, but we will come to the details of these later. I am just trying to give you a flavor of what is coming and how the quantities are related to each other and how they influence your design. So, omega u is G m divided by C. Now we need to add one more refinement to this.

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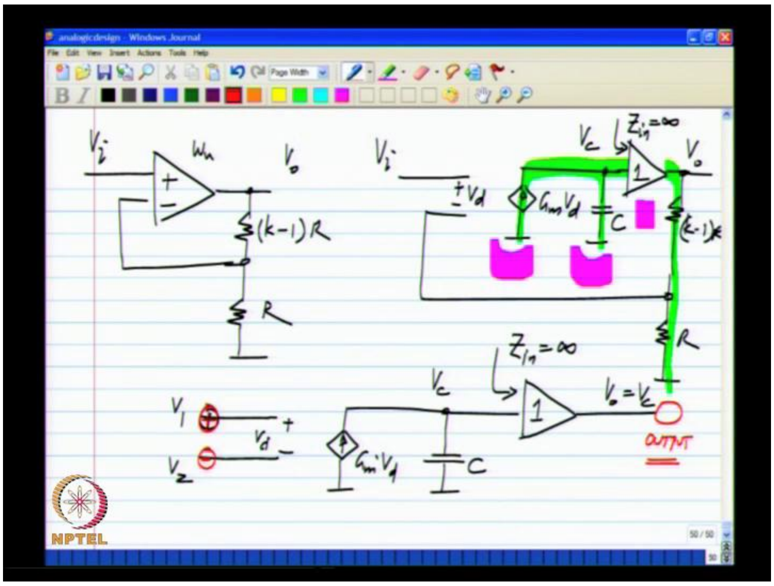

This is our amplifier and the opamp has a unity gain frequency, omega u that is the integrator inside the opamp has a unity gain frequency, omega u. Now you can try to substitute, what we just derived in this case. This is V d, the difference voltage. And goes through a capacitor C and we have the resistive divider here. Now, if you do this, we see that we have actually ruined our integrator, because the way we were getting the integration was by passing the current G m V d through the capacitor.

Now, because you connected the resistances to it, some of the current goes through the resistances, it does not all go through the capacitor. So, in order not to have this, we have to have a voltage buffer. So, again we want worry about implementation at this stage. We will just say that, it is a voltage buffer. That is, V naught will be equal to the voltage across the capacitor, but it will not draw any current, the input impedances infinity. So, our opamp needs a voltage control current source.

Here it needs a capacitor and it also needs a buffer just to isolate whatever you connected the output of the opamp from the internal action of the opamp, because if you connected resistors to the output, then it will not be a good integrator. So, you have to have a buffer which presents an infinity input resistance to the capacitor, so that no current flows into it. All of the current in the control current source has to flow through the capacitor.

So, with this, we have some details of what should be in the opamp. The two inputs are V 1 and V 2 and the difference between them is V d. We need a voltage controlled current source which produce us a current G m V d and drives it through a capacitor. And we need a buffer. A buffer is nothing but, a V c V s, a voltage control voltage source of a gain 1. The output V naught will be equal to V c except that the input impedance of the buffer is infinity.

Now, current flows into the input of the buffer. So, this is our opamp. This is the plus terminal and this is the negative terminal and this is the output. So, there is a practical opamp, which looks exactly like this. We have to use transistors to realize the voltage control current source. We have to also use the transistors to make the voltage control voltage source or the voltage buffer and we will have our opamp.

So, we will go to the transistor level details later, but by studying the opamp at this level, where we have use the symbols for voltage control current source and the voltage buffer will still be able to estimate a lot of non-idealities that will come up in the realization of the opamp. We will see how to make better and better opamp at this level and after that move on to realizing each of these control sources at the transistor level.

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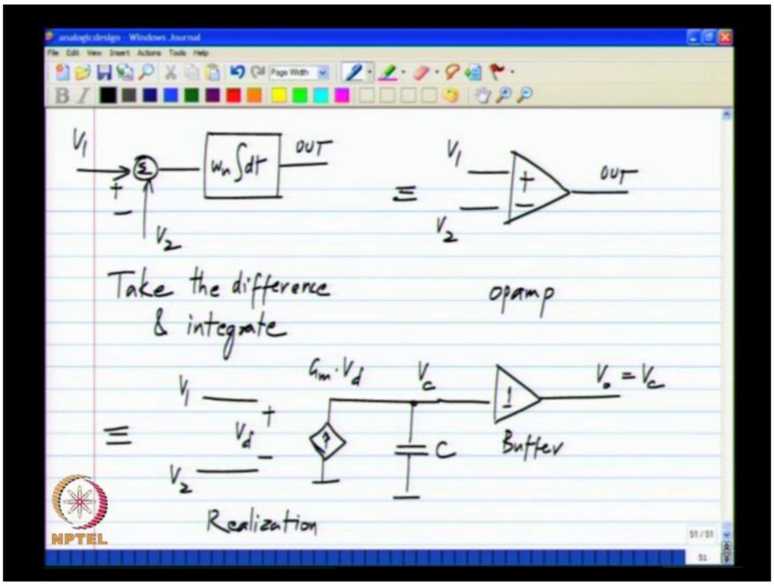

So, this is what we have so far. We have to take the difference and integrate, because we need this for negative feedback. It makes sense to combine all these things into a single block. That was already being done. That is the opamp and a slightly more detailed realization of that is that one. This is the realization of the opamp, not at the transistor level, but at the level of control sources and components.

So, we will study this realization in detail. We will see that this can make an opamp, but there are some obvious non-idealities, that will come up and will also see how to combat them. Now, before you go any further we have looked at, how to realize the opamp at the block level. We will see before we go any further, we have to study one obvious problem with a negative feedback, that is of delay. So, we are being staying. So, for that, for negative feedback, you compare the actual output to the desired output.

Effectively, you do that in case of a speed control. You compare the speed at which you are going. That is the actual speed, to the speed at which you want to go, which is the desired speed. Now in case of the voltage amplifier, you compare V naught by k to V i. Now, what we have left out in this whole comparison is that, there can be a delay in the whole process. Like for instance, let us say the speedometer calculates this speed but with a delay, that is it does not tell you the speed at this particular instant. It tells you the speed which was the speed of the vehicle five seconds ago or two seconds ago.

Whatever it is, there will be a delay. So, in general in any real system there is a delay. The delay could be in computation or propagation of the signal. Whatever it is, there will be delay. So, we have to see the effect of delay on our negative feedback system. So, before we go and analyze the negative feedback system with delay, we can at least try to intuitively figure out what happened. So, let take the same speed control system that we have and let us say that, the speedometer responds with a delay, that is the speedometer does not show you the speed right now. But the speedometer shows you the speed which is five seconds ago. So what happens in that case?

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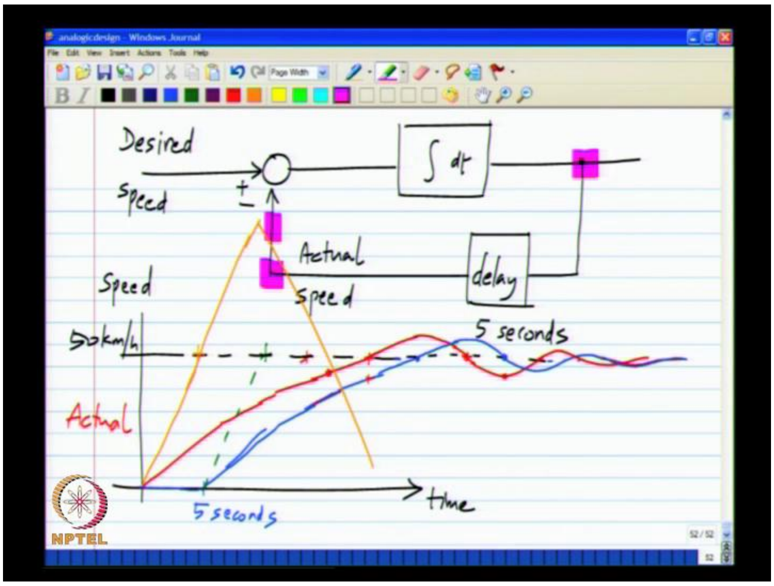

What we were doing was comparing the actual speed to the desired speed and then integrating the difference to result in the actual speed. Now, when we say we are looking at the actual speed, we are sensing the actual speed. What we are doings is simply looking at the speedometer. Now, let say the speedometer responds with the delay. That is the speedometer does not show the current speed, but it shows the speed which was the speed five seconds ago. So, that is the speed, that was the speed of the vehicle five seconds ago.

So, what happens in this case, the obvious thing is that you are responding to not the current speed, but the speed which was five seconds ago. So, let say you start from rest. When you start from rest, you say the speed of the vehicle is zero and the speedometer reading is also zero. The desired speed is 50 kilometers an hour. The x-axis is time. I would like to see what happens over time. So, you start accelerating.

So, the actual speed goes on increasing. So, this is the actual speed, let me make the figure little bigger, I will plot speed versus time. My desired speed is 50 kilometers per hour and I start from rest. Which means that I start accelerating, the red curve is my actual speed, but what am I really sensing at this point? What am I comparing to the desired speed? Not the actual speed, but the actual speed five seconds ago.

So, that means, that I am comparing my desired speed to the actual speed with the delay of five seconds. For five seconds after starting, I do not sense any difference in the speed. So, let say this is a very complicated speedometer, which takes a long time to calculate the speed. So, now after five seconds, the reading of the speedometer starts increasing. Let us say the speed goes on increasing and it reaches fifty kilometers an hour.

So, it does not do it like this, at a constant rate. So, as the feedback appears after five seconds, the actual speed becomes closer to the desired speed and the error reduces. So, what I will do is, at this point, I see that this speed is increasing and I reduce the rate of increase of speed. That I will not be able to see for some more time, I will be able to see it only after five seconds.

So, I will do that and then here I see that the speed has increased and then I reduce the rate further. You have the speed that I am sensing follows also with the delay, but what can happen is the actual speed can reach fifty kilometers an hour, but because you have a delay, the speed that you are sensing, has not yet reached fifty kilometers an hour. It is at some previous value, some value which was from five seconds ago.

So, I reach fifty kilometers an hour and I keep on accelerating, because what I am looking at is not the red curve, but the blue curve. So, and according to the blue curve the speed has not yet reached fifty kilometers an hour. So, I will keep on accelerating and I will go past fifty kilometers an hour and the actual speed will follow, but only five seconds later it tells me that I have gone past fifty kilometers an hour. Oh, so now, I panic. Now I see that, oh I have actually gone past the point that I wanted to.

So, I start decelerating. So, I start decelerating again. There is a delay in might being able to sense that. So, I could go below fifty kilometers an hour. So, and at that point, I do not realize it, but I realize it only five seconds later. It is only at this point, that I realize I have gone below fifty kilometers an hour. So, I accelerate again. So, from this point I accelerate, I do this and probably finally, I will reach fifty kilometers an hour, but it is not in a nice smooth way, that I had earlier.

It is not an a nice smooth way, but I will go past fifty kilometers an hour, below fifty kilometers an hour and so on I will oscillate around fifty kilometers an hour and finally, eventually reach fifty. So, this is a problem now. Of course, the exact extent of the problem depends on how much the delay is. So, if the delay is very large, then there will be a severe problem or the same thing happens, if I try to accelerate very fast. For instance, instead of accelerating gently as shown here that is why accelerator rather violently.

So, the delay is the same, it is still five seconds. So, but I start accelerating like this. Let us see, within five seconds I have a super bike and I reached fifty kilometers an hour. That is very easy with one of these heavy bikes. Now, what happens is, I think, still think that this speed is zero, because my speedometer has not been updated yet. So, I go well past fifty kilometers an hour and then about five seconds after this, I realize that have gone past fifty.

So, then here I start decelerating. So, in fact in this case, it is not clear, if I will ever reach a constant speed, because I am accelerating so fast and I am getting the information so slowly, with so much delay, that I am not sure that if, I will be able to reach a steady fifty kilometers an hour at all. So, there is a problem. So, one problem clearly is that, when you have a delay you tend to overshoot the target. When you have no delay you know exactly when you are coming very close to the target. You go and reducing the rate of increase or decrease, you go on reducing the acceleration. Whereas, if you have a delay, you do not know exactly, when you reach the target.

So, even after you have reached the target, you keep going past the target. That is the problem with delay. And depending on how much the delay is, and how fast you are accelerating, it could be a severe effect. In that I could go severely past the target and then come back and then go severely past the target in the other direction and not reach the target at all or the effect could be mild. That is if I am doing the acceleration gently, it could be that I could do just a little past the target and then little below the target and so on.

So, but whatever it is, this is a phenomenon that has to be investigated to see the exact effect of the delay, because it is not good to have a system where you overshoot past the target and then below and so on. This phenomenon is known as a ringing and you would like to minimize the ringing as much as possible. Now, this other phenomenon showing in the orange curve has severe ringing. You certainly would not like to have this ringing. At least if you have to have ringing, maybe it should be limited to some extent.

So, all this can be quantitatively analyzed by assuming a delay inside the feedback loop. Now, the exact origin of the delay on an electronic circuit can be many. You can have delay in the feedback circuit, you will have parasitic capacitors, because of that you will have delay and so on. So, we will see all those details, but for now we will simply assume the delay of this sort and getting the feedback from the actual to the point of comparison. We have a delay and that delay can cause ringing. Potentially even instability, what I mean by instability is you never reach the target, you keep going way past the target and way below the target.

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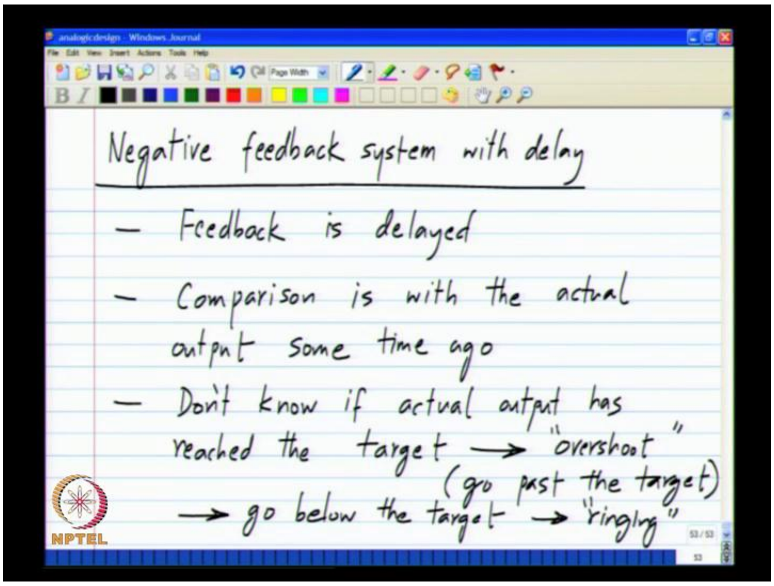

The feedback is delayed, as a result, the comparison is with the actual output, not the current actual output, but the actual output some time ago and because of this, because the comparison is with the actual output, some time ago, you do not realize even if the actual one has reached the target. As a result of this, you overshoot. What is meant by overshoot is you go past the target. Now, once you go past the target, you will get feedback about it.

You will know that, you have gone past the target only sometime later. So, then you start decelerating and then this process continues and you may end up go going below the target. So, this leads to a phenomenon that is known as ringing. How much the ringing, is depends on how much the delay is and how fast you are accelerating. So, the analogy with the vehicle serves you very well here. You can just imagine yourself driving, where the speedometer has a delay and then you can easily imagine the ringing as well. You can also imagine larger delay or a smaller delay or higher acceleration or lower acceleration. You will also see that, the extent of ringing will be different.

So, first of all, there will be a delay in any natural system. So, we have to live with this, but we would not like to have severe ringing. Severe overshoots beyond the target and going below the target and so on. So, at least if there is ringing, we would like to limit it. So, by quantitative analysis of the feedback system with delay, we will be able to do that. So, that we will deal with in the next lecture.